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# WISCONSIN HIGHWAY RESEARCH PROGRAM #0092-45-16

# Field Measurement of Water-Cement Ratio for Portland Cement Concrete – Phase II Field Evaluation and Development

# **Final Report**

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#### **EXECUTIVE SUMMARY**

The water-cementitious material ratio (w-cm) is defined as the ratio by mass of free water to cementitious material in a concrete mix. This ratio controls concrete paste porosity and as a result, has long been viewed as a key mix parameter in determining concrete quality. An accurate, real-time assessment of w-cm in the field is theorized as a means of distinguishing the quality of a concrete mixture and an indication of the final strength of the concrete. If such an assessment were successful, it could provide a very important quality control measure that could be gathered during construction in sufficient time for adjustments to be made in the construction process.

Phase I of this research, performed at the University of Wisconsin-Madison (Santos, 1999), identified two existing methods to rapidly determine the w-cm of fresh concrete. These two methods were the microwave oven method and the Troxler 4430 Water Cement Gauge. Phase II, involved field evaluation and further laboratory development of these same two methods. The Wisconsin Concrete Pavement Association assisted in coordinating site access to highway projects constructed by its member companies. This research topic was targeted based on a research agenda established within WisDOT and reflected recent developments within the concrete community in developing new tools to measure concrete quality.

In this research project, the microwave oven method (AASHTO provisional standard TP23-93) and the nuclear water-cement gauge were evaluated in actual field trials at seven different concrete paving sites as potential methods to rapidly determine the water-cementitious material ratio during construction. Geographically, these sites formed an arc tracing from St. Croix County in the northwest to Rock County in the south-central part of Wisconsin. Two standard Grade A-FA WisDOT mix designs with 19% and 30% fly ash replacement were used at these sites. The coarse and fine aggregates were either igneous-based or limestone depending on the project location. Separate laboratory evaluations were conducted on mixtures using the same materials to provide calibration points.

The microwave oven method relied on precise weighing of a 1500 gram sample of concrete before and after microwave heating. The test result was a moisture content of the sample, which when generalized for the entire batch, provided a water content. The cement and fly ash contents from the batch quantities were combined with the microwave water content to yield a computed water-cementitious material ratio. The nuclear gauge possessed two different radiological sources and sensors that individually measured water content and cementitious material content in ½ ft<sup>3</sup> sample. Repeated measures were made that revealed the inherent error in the method.

Both methods were evaluated based on comparisons with batch quantities. In the field, the water quantities relied heavily on the moisture content of the aggregates. Field measurements of aggregate moisture content occurring once or twice per day were insufficient in some cases to provide a rigorous basis of comparison. In the laboratory, batch quantities including moisture introduced through the aggregates were closely monitored and provided a more reliable basis of comparison. The batch quantities, especially in the field, were also experimental values that contained some level of error. The standard deviation of the error (standard error) was used as the primary measure of error for both methods. According to statistical theory, 68% of the data should lie within one standard deviation of the mean error. The reported errors should be interpreted in light of the fact that even batch quantities, the basis of comparison, also contain some error and thus not all error should associated with the method.

The standard error in predicting the water-cementitious ratio with the microwave oven ranged from 0.014 to 0.030 for individual laboratory mixes and 0.026 to 0.072 for individual field mixes. The mean error for laboratory tests was zero indicating that an experimental result had equal likelihood of being high as low. Since two tests were conducted for each concrete batch, a measure of the inherent test method error was obtained for the microwave oven method. The minimum standard error determined by the repeated tests was 0.023 for laboratory mixes. It was concluded that in general 0.02 is a minimum standard error that can be expected when using the microwave oven method with one sample. Repeated measurements and averaging of the results provided some improvement to the method inherent error.

In the controlled environment of the laboratory, the nuclear gauge method resulted in standard errors of 0.010 to 0.014 for limestone mixes, but the errors for mixes containing igneous aggregates were 0.046 to 0.066. Standard errors of the individual field mixes were generally higher and ranged from 0.012 to 0.089. In all cases, the higher field errors likely were not associated with the method but rather the uncertainty in the moisture content of field aggregates through the course of construction. The distinction in nuclear gauge readings between igneous and limestone aggregates was not as pronounced in the field mix results perhaps because this distinction was masked by the large variability. The data from the two consecutive tests performed on the nuclear gauge revealed the variation inherent in the nuclear gauge method. This within test error in w-cm was 0.018 for limestone mixes and 0.072 for igneous aggregates.

The microwave method was a relative simple method that can be implemented without difficulty. The relatively small sample size (1500 g) used as a single measurement point, however, resulted in an accuracy that is only marginally useful as a quality control method in Wisconsin paving. Repeated measures of the same concrete batch would likely be needed to provide a useful quality control tool. The nuclear gauge method provided satisfactory predictions of water-cementitious material ratios for those concrete mixtures using limestone aggregates. It is unknown why igneous aggregates resulted in poor gauge performance. Given the training required to use the nuclear gage, the need for extensive laboratory calibration and the unexplained performance with igneous aggregates, the nuclear gauge is not ready for general use in Wisconsin concrete pavement construction.

# **Table of Contents**

	Ackno	owledgments	ii
	Discla	nimer	ii
	Techr	nical Report Documentation Page	iii
	Execu	tive Summary	iv
1	Intro	duction	1
	1.1 S	ignificance	1
	1.2	Objective	1
	1.3 S	cope of Work	1
		ackground and Relevant Literature	
	1.4.1	Microwave Oven Method	
	1.4.2	Troxler Water Cement Gauge	2
2	Metho	odology	3
	2.1 N	Aicrowave Oven Method	3
	2.2 N	Nuclear Gauge	4
	2.3 F	Field Testing	5
		tatistical Analysis	
3	Micro	owave Results	10
	3.1 L	aboratory Results	10
	3.1.1	Minimum Error (Test 1 vs. Test 2)	10
	3.1.2	INDOT Correction Factor	
		Correction Factor for Mortar Content	
	3.1.4	Correction Factor using Measured vs. Actual W-cm	
	3.1.5	Standard Error	
		Field Microwave Results	
	3.2.1 3.2.2	Minimum Error (Test 1 vs. Test 2)	
	3.2.3	Variable moisture contents of aggregates	
	3.2.4	Mean and Standard Error	
4	Nucle	ar Gauge Results	2.2
-	11441	HI SHULV INCHIN	

4	4.1 I	ntroduction	22
	4.1.1		
4	4.2 N	Nuclear Gauge Laboratory Results	22
	4.2.1	Cement Probe	
	4.2.2	Difference Between Phase 1 and Phase 2 Calibration Slopes	23
	4.2.3	Water Probe	25
	4.2.4	Water-Cementitious Material Ratio	
	4.2.5	Alternative Calibration – Pure Tests	27
4	4.3 N	Nuclear Gauge Field Results	28
	4.3.1	Cement Probe	28
	4.3.2	Water Probe	
	4.3.3	Water-Cementitious Material Ratio	29
5	Stren	gth Results	29
	5.1 L	aboratory Strength Results	29
	5.2 F	Field Strength Results	32
6	Sumn	nary and Conclusions	35
(	6.1 S	Summary of Microwave Oven Method Results	35
(	6.2 N	Aicrowave Oven Recommendations	36
(	6.3 S	Summary of Nuclear Gauge Results	36
(	6.4 N	Nuclear Gauge Recommendations	36
(	6.5	Conclusions	37
7	Litera	ature Cited	38
Im	nlamen	tation Plan	11

#### 1 Introduction

#### 1.1 SIGNIFICANCE

The water-cementitious material ratio (w-cm) is defined as the ratio by mass of free water to cementitious material in a concrete mix. This ratio controls concrete paste porosity and as result, has long been viewed as a key parameter in determining concrete quality. Numerous studies dating back to that by Abrams (1918) have correlated a decreased water-cementitious material ratio with increased strength. The American Concrete Institute's method of mix design controls the w-cm with consideration to both target strength and durability.

Early water-cement ratio (w-c) research dealt with concrete that only contained Portland cement as the cementitious component. In addition, the w-c was viewed primarily as a control on compressive strength. More recently, linkages to durability have been investigated and the role of the w-c or w-cm parameter has become less clear as a wide variety of pozzalans or cementitious materials are combined with Portland cement. None-the-less, the water-cementitious material ratio is deemed as a primary mix control parameter and concrete experts have called for the development of a method to measure the w-cm of fresh concrete (Neville 1999). An accurate, real-time assessment of w-cm in the field is theorized as a means for distinguishing the quality of a mix and an indication of the final strength of the concrete.

Phase I of this research performed at the University of Wisconsin-Madison (Santos, 1999) identified two methods to rapidly determine the wcm of fresh concrete. These two methods were the microwave oven method and the Troxler 4430 Water Cement Gauge. Previous research included testing concrete in laboratory conditions.

#### 1.2 OBJECTIVE

The objective this research was to assess in actual field conditions the accuracy and application issues of the Microwave Oven Method (AASHTO TP-23, 1993) and the Troxler Water Cement Gauge (Troxler, 1993) for measuring the water- cementitious ratio (w-cm) of fresh concrete. From conversations with concrete professionals, an error threshold of about 0.01 or 0.02 was established a priori as an accuracy level that would be of use as a real-time indication of the concrete quality.

#### 1.3 SCOPE OF WORK

This Phase II research extended the assessment of the Microwave Oven Method and the Troxler Water Cement Gauge to fieldwork. Testing was completed at seven concrete paving sites with four different concrete paving contractors. Two standard Grade A-FA WisDOT mix designs with 19% and 30 % fly ash replacement were used at these sites. The coarse and fine aggregates were either igneous or limestone depending on the project location. . Geographically, these sites formed an arc tracing from St. Croix County in the northwest to Rock County in the south-central part of Wisconsin. The individual concrete materials were returned from each job site to the Wisconsin Structures and Material Test Laboratory (WSMTL) for calibration of the nuclear gauge.

Laboratory testing was performed with the goal of determining the calibration equations for the nuclear gauge and to further determine the errors associated with each method. Laboratory testing also included the investigation of alternate methods to calibrate the nuclear gauge.

#### 1.4 BACKGROUND AND RELEVANT LITERATURE

Phase I of this study performed at the University of Wisconsin-Madison (Santos and Cramer, 1999) identified two methods to rapidly determine the w-cm of fresh concrete. These two methods were the microwave oven method and the Troxler 4430 Water Cement Gauge. After selecting the two methods for study from possible methods that use current technology, Phase I research focused on evaluating the methods by testing concrete in laboratory conditions. The mixes studied had varied w-cm and were tested at three different environmental temperatures and at two hold times. It was concluded that environmental temperature and hold time did not affect the results of the microwave method or nuclear gauge. The results revealed standard errors for the microwave oven method and nuclear water cement gauge method to each fall within the range of 0.02 to 0.04. These standard errors were deemed to be on the high side for possible implementation. But the work also began to reveal that the actual w-cm varies with the sampling of the concrete and all error cannot be attributed to the measurement method. In fact the methods were deemed to hold promise for detecting w-cm variations within batches of concrete that previously have been undetectable. Sufficient potential for further development to resolve these issues as well as the need to establish field viability prompted the undertaking of the Phase II research reported herein.

#### 1.4.1 MICROWAVE OVEN METHOD

Previous studies demonstrated that a microwave oven could be used to gravimetrically determine the water content of a concrete sample (Halstead, 1993; Nagi and Whiting, 1994). According to Abrams' Law (Abrams, 1918) the strength of concrete is inversely related to the water-cement ratio of the sample. The water-cement ratio is calculated using the free water in a mix and should exclude the water absorbed by the aggregate. The cement content as reported by the batching equipment or some other weighing process is assumed to be reliable and is not directly measured. The water-cement ratio is thus determined by calculating the water lost during microwaving and the cement content reported by the batch plant. Various studies of the microwave oven method report that the water contents determined from two properly conducted tests by the same operator on the same material should not differ by more than 7.6 lb/yd<sup>3</sup> (AASHTO TP23-93, Nagi, 1994). Some theorized causes of this variation include cement hydration, sampling errors, and moisture variations in the aggregate. According to an Indiana Department of Transportation study of the microwave method (Nantung, 1998), ordinary Portland cement does not produce sufficient amounts of hydration products to have a significant effect on the amount of water recovered in the short amount of time it takes to complete a test. In addition, INDOT proposed a correction factor to adjust the water content reported for sampling errors. It was thought that a sample with a higher than average portion of aggregate would have less mortar and correspondingly less water. The correction factor adjusts the watercement ratio reported based on the amount of coarse aggregate present in the sample. Halstead (1993) reported that moisture variation in the aggregate led to significant variability in the watercementitious material ratio.

# 1.4.2 TROXLER WATER CEMENT GAUGE

The Troxler 4430 Water Cement Gauge determines the water and cement contents of a concrete mix using radiological principles and two separate probes. A number of factors have been found to affect the accuracy of the gauge. The air content of the concrete mix affects the density of the concrete. Large variations in air content were found to have a negative effect on

the accuracy of the gauge readings (HITEC, 1996). To reduce this source of error, the gauge manufacturer recommended that test batches be controlled to  $\pm$  1% of the target air content. Additional factors found to affect the gauge reading were the type of aggregate and fly ash used in the mix (HITEC, 1996). The cement probe was found to detect the heavy metals present in igneous aggregate types affecting gauge readings. The variation in calcium content in different classes of fly ashes also resulted in fluctuations in the cement probe readings. To combat this source of error, a full calibration is recommended for each mix design and set of materials. Literature available on the Troxler Water Cement Gauge reported that the cement probe is capable of determining cement content to within 18 to 45 lb/yd³ (Whiting, 1999 and HITEC, 1996). The water probe is reported to be capable of determining water content to within 2 to 4 lb/yd³. These errors in water and cement contents translate into an error of 0.03 in w-cm.

#### 2 METHODOLOGY

#### 2.1 MICROWAVE OVEN METHOD

The microwave oven method (AASHTO provisional standard TP23-93) was used to determine the water content of fresh concrete using a 900 W microwave oven to evaporate water from the sample. Using the weight of the sample before and after microwaving, the water content can be calculated. In order to obtain the w-cm of the batches, the cementitious material contents from the field batch sheets were used. This procedure cannot be used on any concrete with metal constituents as metal is incompatible with the operation of a microwave oven.

For each batch of concrete, two tests were performed to investigate sampling differences and errors inherent in the test method. Care was taken to obtain a representative sample of the concrete. Each sample of concrete was obtained individually, placed in a glass dish, wrapped with the fiberglass cloth, and tested in the following manner:

- Weigh the dish and fiberglass cloth. Record this value as WS.
- Sample concrete, place  $1500 \pm 100$  grams in dish. Wrap the sample in the fiberglass cloth and weigh. Record this value as WF.
- Microwave the sample for a period of 5 minutes at the 900 W power setting.
- Remove the sample from the microwave, unwrap, and grind the sample to break the sample apart to encourage thorough drying, rewrap the sample, and return it to the microwave.
- Microwave the sample for a period of 5 minutes at the 900 W power setting.
- Remove the sample from the microwave, stir, and weigh the sample.
- Microwave in 2-minute cycles until difference in weight is less than 0.1 <sup>1</sup>grams. Record the final value as WD.

Occasionally an aggregate was included in the sample that had high metallic contents. Small pieces of metal attract the microwaves causing excessive heat gradients. There is a tendency for individual pieces of aggregate to get very hot, glow red, and fracture. This could damage the equipment and be a threat to the operator. When glowing aggregates were observed,

<sup>&</sup>lt;sup>1</sup>The procedure outlined in AASHTO TP-23 was followed in this study with exception to the determination of the endpoint of the test. In an attempt to increase accuracy of the test method, the sample was dried in the microwave until the weight differential was 0.1 g. For comparison of these test results with previous studies, the weight loss when the weight differential reached 0.5 g as specified in the specification could be calculated.

the power setting was reduced on the microwave to minimize material loss due to the fracturing aggregate.

When the sample had sufficiently cooled, the samples were sieved to obtain the percentage of coarse aggregate and mortar sampled. In a concrete sample, the majority of the water is located in the mortar. By inspecting the proportions of aggregate and mortar in a small microwave sample in relation to the large concrete batch, insight is provided into the deviations from the expected w-cm. For example, a microwave sample with proportionally high aggregate content would be expected to display a lower water content than the batch as a whole.

For each microwave test the water content of the mix was computed using the fresh and dry weights of the concrete sample (Equation 2.1-1).

$$Water(\%) = \frac{WF - WD}{WF - WS}$$
Eq. 2.1-1

Where WF = Mass of Dish, Cloth, and Fresh Concrete

WD = Mass of Dish, Cloth, and Dry Concrete

WS = Mass of Dish and Cloth

The percent of water in the sample can be translated into the water content in units of pounds per cubic feet for the concrete tested by using the unit weight of the concrete (Equation 2.1-2).

Water 
$$\left(\frac{lb}{ft^3}\right)$$
 = Water (%) · UW  $\left(\frac{lb}{ft^3}\right)$  Eq. 2.1-2

Where UW = the Unit Weight of the concrete batch

In the previous research, the concrete sample was dried in the microwave until the weight was within 0.5 grams of the previous reading. In this study the decision was made to carry the test out until the weight was maintained within 0.1 grams to improve the accuracy of the test. By continuing the test to 0.1 grams, the length of the test increased approximately 50% to 30 minutes. From the data taken to 0.1 gram accuracy, the weight of the sample within 0.5 grams could still be recovered and calculations were done to compare the accuracy of the two readings. For all of the following attempts at correcting the microwave readings in the field and lab, calculations were done using 0.1 and 0.5 gram accuracies. The calculations using tests taken to 0.1 grams resulted in lower average standard errors (Appendix B.4). Therefore, only the results obtained on the basis of the 0.1 gram difference microwave readings were reported here.

#### 2.2 NUCLEAR GAUGE

The Troxler Water Cement Gauge (Troxler, 1993) consists of two probes, each working on separate radiological theories. The probes are individually placed into a ½ft³ sample of concrete for a period of time and measurements recorded. The water probe contains a sealed source of californium-252. The neutrons emitted by the probe are thermalized, or slowed, by the hydrogen in the concrete sample. A detector in the water probe counts the thermalized neutrons. Since the hydrogen detected is assumed proportional to the water in the mix, there exists a positive relationship between the number of thermalized neutrons detected and the water content of the concrete in the bucket.

The cement probe contains a sealed source of americium-241. Photons emitted by this probe are likely to be absorbed by elements with atomic numbers higher than 14. Most elements present in concrete have atomic numbers lower than 14 with the exception of the calcium present

in the cement. Calcium has an atomic number of 20 and is much more likely to absorb the protons from the americium source. For this reason a concrete mix with high cement contents will absorb the protons readily and will result in fewer protons available for the detector to record. A low cement count corresponds to high cement content. Some aggregates contain trace amounts of iron or other metals with high atomic numbers. A calibration must be performed with each aggregate type in order to account for the base reading of the materials in the mix.

The nuclear water-cement gauge requires a laboratory calibration in order to interpret the readings taken in the field and to account for the base gauge reading of the materials. The calibration recommended by the gauge manufacturer involves testing eight batches of concrete with known variations in cement and water content. The mixes required for a laboratory calibration are as follows:

• Target (4): proportionally same mix design as in the field

• + Cement: 100 lb/yd<sup>3</sup> more cement than target mix

• - Cement: 100 lb/yd<sup>3</sup> less cement than target mix

• + Water: 7% more water than target mix

• - Water: 7% less water than target mix

These calibration mixes must be performed for each mix design and for each change in mix materials. Since the cement probe detects elements with high atomic numbers, the aggregates used in a mix may contain traces of elements with high atomic numbers that the gauge will detect. A calibration of both probes and the resulting calibration lines relate detector count ratios for each mix design to changes in water and cement content independent of the base reading of the aggregates. In order to complete the calibration mixes for the paving sites that were visited, materials were collected and returned to the Wisconsin Structures and Materials Testing Laboratory (WSTML) at the University of Wisconsin – Madison.

Use and transportation of the nuclear water-cement gauge falls under the jurisdiction of the U.S. Nuclear Regulatory Commission (NRC). Operators must receive approximately 4 hours of training, pass a qualification exam and be certified to operate the gauge. Transporting the gauge within the State required further training (approx. 4 hours), a qualification/certification exam and special record keeping and conduct. The Wisconsin State Patrol and NRC check compliance with the transportation regulations. Lack of compliance can result in loss of certification and the ability to use the gauge. The University complied with these requirements during the conduct of this research.

#### 2.3 FIELD TESTING

Field-testing of the microwave oven method and the Troxler water cement gauge took place during the summers of 1999 and 2000. During spring 1999, surveys were distributed to various concrete pavement contractors throughout Wisconsin inquiring about paving locations, duration of paving, and aggregate types to be used. The information on these surveys was used to schedule site visits. Attempts were made to choose projects with different mix designs and aggregate types (Table 2-1) in a variety of locations across Wisconsin. Seven field paving project sites were visited (Figure 2-1). Two sites (Fond du Lac County) were on the same general project and location but these visits occurred three months apart. A generator, two microwave ovens, the Troxler water cement gauge, and standard plastic concrete testing

equipment were transported to each site. The materials used in each mix were returned to the Wisconsin Structures and Material Testing Labs in Madison for further testing and calibration.

**Table 2-1: Characteristics of Field Mixes** 

Site	Number of Concrete Batches Tested in the Field	Mix Grade	Aggregate Type
Α	3	A-FA	Limestone
В	4	A-FA	Limestone
C	15	A-FA 30	Limestone
D	14	A-FA 30	Igneous
Е	3	A-FA	Limestone
F	4	A-FA	Igneous
G	3	A-FA 30	Igneous

At each testing site, a number of standard plastic concrete tests were completed in addition to the microwave oven and the nuclear water cement gauge tests (Table 2-2). The batch sheets were collected for each concrete load tested in addition to information about hauling distance from the batch plant to the paving site. For each batch of concrete, the temperatures of the concrete and the environment were taken. Testing performed on each load of concrete included, a fresh air content, unit weight using a ¼ ft³ bucket and the ½-ft³ nuclear gauge bucket, slump, and the casting of 28-day compression cylinders. The 6-inch by12-inch cylinders remained on site for 24 hours to 3 days depending on the paving site and the duration of the study at the particular site.

**Table 2-2: Tests Performed at Each Job Site** 

Tests Performed in Field	<b>Test Designation</b>
Temperature of Concrete	ASTM C 1064
Temperature of Environment	-
Unit Weight	ASTM C138
Plastic Air Content	ASTM C 231
Slump	ASTM C 143
28-day Compression Cylinders	ASTM C 39
Microwave Test	AASHTO TP23-93
Nuclear Gauge Test	Troxler Users Manual
Batch Information	-
Moisture Contents of	ASTM C 566
Aggregates (Project G only)	AS 11VI C 300

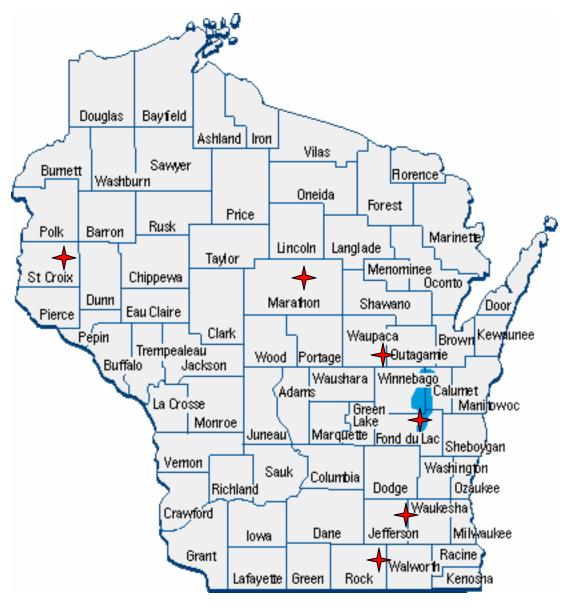


Figure 2-1: Map of Wisconsin – Concrete Paving Sites Visited

At each concrete paving site, the testing regimen remained as constant as possible given environmental factors. Details as to where the equipment was set up and how the concrete was delivered varied, but general details follow. Once the concrete was delivered, the temperatures of the concrete and the surrounding environment were immediately recorded. The temperatures varied during the day as testing started early in the morning and continued through late afternoon. Additionally the plastic air content varied throughout the day due to the varying temperature, variation in moisture content of the aggregates, and changes in mix design.

After some refinement of the testing order, it was found that the tests for each concrete batch required 1 ½ hours. Including time for equipment set-up, time waiting for the concrete to

arrive, and clean up, it was found that 3 to 5 tests could be completed each day with this research protocol. Additional delays in testing occurred due to equipment problems, weather concerns, and delays in paving.

At the final paving site visited (Project G) some tests were performed at the batch plant in addition to testing at the paving site. At the batch plant, a concrete sample was dispensed from the truck and a microwave sample was immediately taken. This sample was placed in the microwave dish and sealed to prevent moisture loss during transport. Samples of the aggregate were also taken for moisture content determination before each batch was tested at the batch plant. One operator then followed the truck to the paving site. At the paving site, another concrete sample was dispensed from the same truck and the standard testing commenced. A third person stayed at the batch plant and performed a unit weight test, plastic air content test, slump, and prepared strength cylinders. In this testing, transport time and placement conditions were noted to determine possible influences on the microwave readings.

#### 2.4 STATISTICAL ANALYSIS

The standard deviation of the error or standard error (SE) of each data set was computed and used in this study to quantify the difference between the measured w-cm and the expected ("actual") w-cm. (Equation 2.4-1). The expected w-cm for each batch was taken from the batch sheets, which were not truly "actual" results. Errors associated with the batch sheet quantities were potentially due to fluctuation in the moisture content of the aggregates, weighing accuracy and within batch w-cm variations. The moisture content of the aggregate varied throughout the depth of the aggregate pile due to evaporation. Typically, the moisture contents were tested twice daily at the batch plant. Due to the variation of the moisture within the aggregate pile and the frequency of the moisture tests, errors were likely introduced. In this fashion, the batch contents reported at the batch plant are experimental values that also contain error. In this research, the two experimental methods to determine the w-cm, the microwave and nuclear gauge, were compared to another experimental value, the batch sheet quantities. In the laboratory where conditions can be carefully controlled, the batch quantities are expected to contain less error than in the field.

$$SE = \sqrt{\frac{\sum (Measured - Batch)^2}{n}}$$
Eq. 2.4-1

where SE = standard error,

Measured = measured w-cm from the microwave or nuclear gauge method

Batch = computed w-cm from batch weight information

N = number of comparisons

In typical statistical analysis of experimental treatments to a population, the standard error is calculated with the numerator as the sum of the square differences between the experimental result and the mean result and the denominator as the number of samples minus 1 (n-1) (Devore, 1995). The term subtracted from the denominator represents the number of terms in the calculation of the numerator that are averaged. The widely used standard error calculation assumes that the "actual" value is calculated as the mean of all of the test samples. For this study each experimental value was compared to another experimental value reported by the batch

sheets, not an average of all of the readings. Therefore the denominator of the standard error calculation was simply the number of tests completed (Equation 2.4-1).

According to statistical theory, for a normally distributed set of data, 68% of the data should lie within one standard deviation of the mean error. In order to improve the accuracy of this confidence interval a range of two standard deviations from the error are used to yield a confidence of 95% (Figure 2-2). The typical range of wcm in concrete pavement is 0.40 to 0.50. While the confidence interval of  $\pm$  2 SE's provides a higher level of confidence, the resulting error range becomes too large to be useful. The standard error (1 standard deviation) was adopted in this research to reflect the error associated with a method.

The mean error of a test method, or the error that is most likely to occur, was an important tool in determining the adequacy of a method. It was desired to develop methods that have a mean error of zero. A test method with a mean error of zero indicates that the errors are randomly scattered and would be likely average out if multiple tests were performed on a mix.

Based on input from WisDOT staff and industry experts, we targeted a threshold standard error of 0.02 to assess the usefulness and potential of the w-cm methods. Higher standard errors would lead to uncertainty and would not be an improvement upon currently accepted quality control methods. The mean error of the results was also inspected in order to assess the bias of a method.

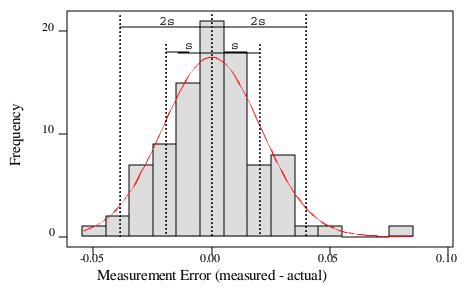


Figure 2-2: Histogram with Normal Distribution Curve

## 3 MICROWAVE RESULTS

The microwave oven method of determining the water-cementitious ratio of fresh concrete was found to be a simple procedure that provided reasonable accuracy. Testing took under 30 minutes and gave reasonably accurate results in the laboratory. A number of correction factors were investigated to account for observed trends in the data and to lower the overall standard error. Correction factors studied accounted for sampling errors and the amount of water that the microwave was able to recover during the short duration of the test. Focus was first placed on the laboratory data as the possible sources of error were minimal and the batch quantities of all materials added to the mix were precisely known.

The standard errors of the w-cm predicted by the microwave oven method were calculated for each project using Equation 2.4-1. The average standard error for mixes completed in the laboratory and the field was 0.030 after a correction factor was applied. The standard error of the laboratory mixes ranged from 0.014 to 0.030 with an average of 0.027. The field standard error was higher ranging from 0.026 to 0.072 with an average of 0.037. Based on the testing of the moisture content of the aggregates at a batch plant, it was theorized that the greater variation of w-cm in the field was primarily due to variations in the moisture content of the aggregates. When the standard errors of the laboratory mixes were compared to the within test standard error, it became apparent that the majority of the errors experienced with the microwave oven method are inherent to the method. These errors are most likely associated with the sampling method used for the test. The sample size used for the test is small in proportion to the whole batch resulting in a sample that may not always be representative of the batch. However, a larger sample size was not used as the test would have taken longer and would have been less practical for field use. It is theorized that the microwave oven method is accurately detecting the moisture content of the small sample and that the standard errors represent sampling errors and errors in the batch weights.

#### 3.1 LABORATORY RESULTS

# 3.1.1 MINIMUM ERROR (TEST 1 VS. TEST 2)

Two microwave samples were taken and tested from each batch of concrete in the field and in the laboratory. These two microwave samples were obtained from the same 2-ft<sup>3</sup> sample of concrete and tested consecutively in separate microwave ovens. Care was taken to obtain each sample with representative amounts of cement paste and aggregate. The same researcher performed all of the microwave tests to eliminate operator-biased errors. Even though care was taken in the sampling method, the two microwave samples consistently yielded different w-cm values. The two w-cm results were compared to one another using ANOVA statistics (Dowel 2001). While the analysis of the two microwave tests demonstrated that there was no significant difference between the consecutive tests in the field or in the laboratory, some variability in the w-cm results was observed. The first test was compared to the second test and the standard deviation of the error between them was determined. This value is referred to as the within test standard error and is theorized to be the minimum error attainable with the microwave oven method. The within test standard error for all laboratory mixes was 0.023. This value represents the inherent variation present in the microwave oven method due to sampling errors and errors present in the method.

#### 3.1.2 INDOT CORRECTION FACTOR

The microwave method relies on a representative sample of concrete to accurately predict the water present in the mix. If a microwave sample contained a larger than representative amount of aggregate in the constant 1500 gram sample, there should have been a smaller than representative amount of paste. Since the majority of the water in the mix was assumed to be in the paste, the corresponding water content that was found by microwaving the sample should be lower than that of the mix. To account for this possible sampling error, a correction factor developed by the Indiana Department of Transportation was investigated.

Previous research by the Indiana Department of Transportation (Nantung, 1998) suggested the use of a correction factor to address errors in the sampling of concrete for the microwave oven method. By sieving the sample after testing, the amount of aggregate in the sample can be calculated. The correction factor developed by INDOT (Equation 3.1-1) is multiplied by the water-cementitious ratio determined by the microwave method.

$$CF = \frac{\left(1 - CA_{batch}\right)}{\left(1 - CA_{sample}\right)}$$
 Eq. 3.1-1

Where  $CA_{batch}$  = percent of coarse aggregate in batch

CA<sub>sample</sub> = percent of coarse aggregate in microwave sample

When the INDOT correction factor was applied to this study, the benefits were questionable. The correction factor did not consistently improve the predicted water-cement ratios of microwave method and the corresponding standard errors increased for most jobs. The average standard error for all jobs increased from 0.029 to 0.031 when the INDOT correction factor was applied (Table 3-1). The INDOT correction factor did slightly improve the standard error of the laboratory results (from 0.031 to 0.025) but had a negative effect on the field measurements (0.028 to 0.036).

Table 3-1- Uncorrected Microwave Oven Method Standard Errors

Project	All	Field	Laboratory
A	0.036	0.056	0.029
В	0.031	0.034	0.028
С	0.026	0.030	0.018
D	0.026	0.021	0.031
E	0.027	0.025	0.028
F	0.038	0.042	0.035
G	0.020	0.019	0.020
Average	0.029	0.028	0.031

Table 3-2- INDOT (	Corrected Microwave	Oven Method	Standard Errors
--------------------	---------------------	-------------	-----------------

Project	All	Field	Laboratory
A	0.038	0.067	0.016
В	0.044	0.051	0.031
С	0.024	0.025	0.021
D	0.026	0.021	0.031
Е	0.038	0.032	0.016
F	0.031	0.024	0.036
G	0.037	0.068	0.019
Average	0.031	0.036	0.025

#### 3.1.3 CORRECTION FACTOR FOR MORTAR CONTENT

In order to diagnose the source of this problem with the INDOT correction factor, plots of the mortar content vs. the microwave oven readings were inspected. The difference between the mortar that was measured by sieving the sample after the microwave test was complete (M = measured mortar content) and the amount of mortar in the mix as reported by the batch sheets (A = actual mortar content) was computed. This term represents the error in the amount of mortar sampled in the microwave method. In a similar manner the error in w-cm was computed. The error in mortar content was then plotted against the error in w-cm. In Figure 3-1, the INDOT correction factor was used in computing the measured w-cm. Although the correlation is weak, the correlation line displays a negative slope indicating that if the sample has more mortar than the batch sheets indicate, the w-cm reported had a tendency to be lower than the batch sheet values. This contradicts logic since the water in the sample is assumed to be primarily in the mortar.

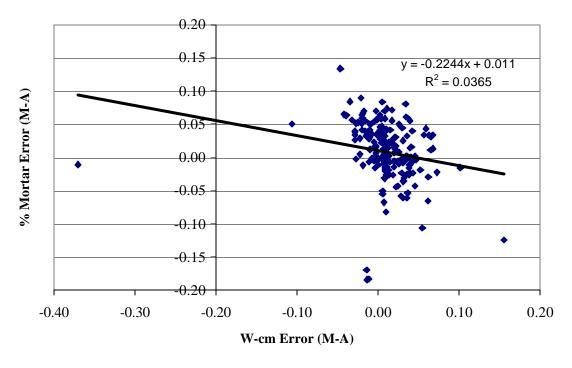


Figure 3-1: Microwave Oven Method: Percent Mortar Error vs. INDOT Corrected W-cm Error - All Data

The data was again plotted using the uncorrected water-cementitious ratio (Figure 3-2). This plot displays a positive slope. Furthermore, as the data were split into individual projects, a clear correlation emerges between the amount of mortar in the sample and the water-cementitious ratio measure. It appears from these data (Dowell, 2001) that there is a relationship between the mortar content of the sample and the w-cm, but the INDOT correction factor is not adequately correcting for this phenomenon.

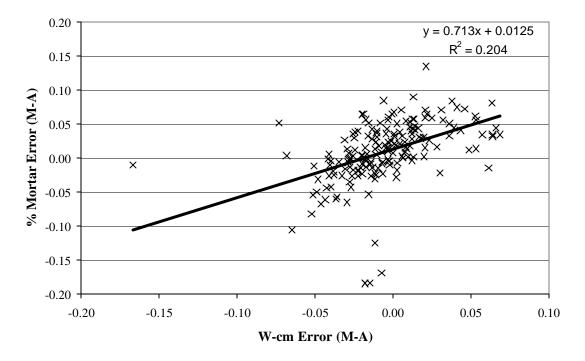


Figure 3-2: Microwave Oven Method: Percent Mortar Error vs. Uncorrected W-cm Error - All Data

#### 3.1.4 CORRECTION FACTOR USING MEASURED VS. ACTUAL W-CM

In the search for a correction factor to apply to the water-cementitious ratio determined by the microwave oven method, differences between measured and actual w-cm data were observed. For each microwave test the measured and actual water-cementitious ratios were calculated and plotted against each other (Figure 3-3). A line at a 45° angle represents perfect correlation between the measured and batch sheet data for the water-cementitious ratio. Many of the mixes displayed high recovery values. Since the measured w-cm was plotted on the y-axis against the actual w-cm on the x-axis, the points representing high water recovery appeared above the line of perfect agreement. These test samples lost more weight during the microwave cycles than that of the moisture present in the mix according to the batch sheets.

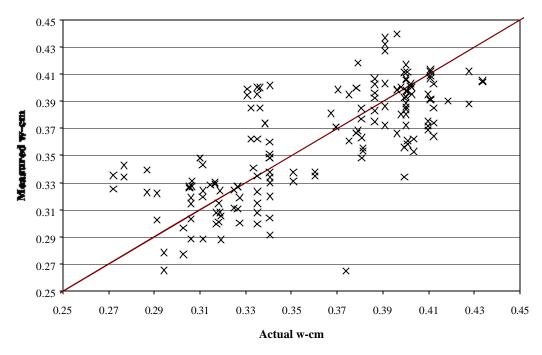


Figure 3-3: Measured vs. Actual W-Cm (Uncorrected Microwave Data)- All Data

When the data were split into field and laboratory tests and it was observed that many of the laboratory mixes had average recovery values less than 100% (Figure 3-4). The aggregate was dried before mixing so that the amount of water added to the mix, and thus available for recovery by the microwave method, was precisely known. It was assumed that that not all the water in a sample would be recovered during the brief testing cycle since some would be absorbed by the aggregate and rendered unrecoverable during the short testing period. The average water recovery was 94% for all microwave tests completed in the laboratory. The average error of 0.016 was then added back into to all calculated water-cementitious ratios as a correction constant to bring the average water recovery to 100%. When this adjustment was applied, the standard errors for all of the lab data decreased to an average of 0.027 (Table 3-3).

To identify a strategy to reduce the sampling error with the microwave oven method, the two microwave results from each batch of concrete were averaged. This average w-cm result was then compared to the batch sheet and the standard errors were calculated (Table 3-3). The standard errors decreased for all of the projects when the average microwave w-cm was used. This supports the theory that much of the error in the method is due to sampling errors. It is expected that the errors would further decrease if more samples were taken from each batch of concrete.

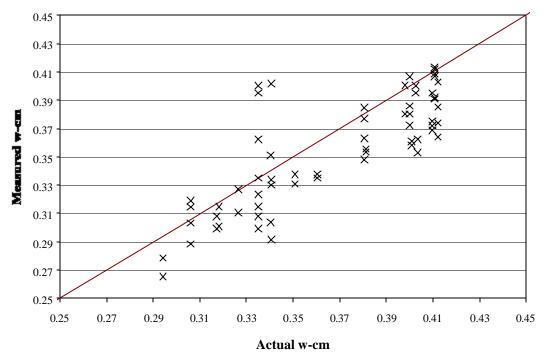


Figure 3-4: Measured vs. Actual W-Cm - Laboratory Data

#### 3.1.5 STANDARD ERROR

The standard deviation of the errors between the actual and measured water cementitious material ratio was calculated. This value is referred to as the standard error (Table 3-3). According to statistical theory, 68% of the data should lie within one standard deviation of the mean for data with a normal distribution. The standard error is used as a measure of the accuracy of the method. The standard errors for the laboratory data vary, but no significant trend between igneous and limestone aggregates or mix design was observed. The variation is most likely due to small sample sizes that do not accurately represent the mix as a whole. The standard deviations decreased as the two microwave samples from the same batch of concrete were averaged. This further supports the theory that the errors are due to sampling variations.

Table 3-3: Laboratory Microwave Oven Method Standard Errors

Project	Laboratory SE	Average of Test 1 & Test 2 SE
A	0.018	0.017
В	0.018	0.017
С	0.014	0.011
D	0.025	0.023
Е	0.018	0.017
F	0.030	0.023
G	0.015	0.010
All	0.027	0.017

# 3.2 FIELD MICROWAVE RESULTS

# 3.2.1 MINIMUM ERROR (TEST 1 VS. TEST 2)

The results from the two microwave samples taken from the same 2-ft<sup>3</sup> concrete sample were compared and the minimum standard error was established for the field. The minimum test standard error for field mixes was 0.038. Since the two microwave samples were taken from the same batch, the errors primarily represent the variation in sampling. The minimum test standard error was higher in the field than in the laboratory indicating that field measurement introduces additional variation. This variation could be due to segregation within the batch, evaporation, a longer hold time, or environmental conditions.

#### 3.2.2 HIGH FIELD RECOVERIES

The standard errors between the measured and batch sheets experienced for the field tests were higher in most cases than the laboratory tests. The same correction factors were investigated for the field projects as the laboratory projects. Trends were observed and dealt with in a similar approach as with the laboratory test analysis. Most of the laboratory data were less than the line of perfect agreement indicating that slightly less than all the water in the mix was recovered. Contrasting with the lab data, some of the field data plotted higher than the line of perfect agreement (Figure 3-5). This indicates that more water was recovered by the microwave method than was present in the mix according to the batch sheets. When the correction factor that was developed in the laboratory for low recovery of the microwave was applied to the field mixes, the standard errors increased. However, the factor remained in calculations as the theory behind it applies to any test done in the microwave oven, regardless of testing location. Recovery values greater than 100% in field tests led to the conclusion that the errors were due to the additional sources of variation found in field conditions. This error could be explained by sampling errors, material lost during the microwave test, changes in aggregate moisture content, or batching errors.

One final day of testing (Project G) in the field seemed to isolate a likely source of error. During testing at the site of Project G, the moisture contents of the aggregates were taken before each batch was mixed. Additionally, to study the relationship between testing location, and possible segregation problems during transport, critical tests were performed at the batch plant and at the paving site for the mixes tested (Table 3-4). This testing was performed in July with a maximum temperature in the low 80°s F and with haul distance between batch plant and paving site of 3 miles. Upon completion of an ANOVA analysis of the data from Project G, it was concluded that the results from testing at the batch plant were not significantly different from the results at the paving site (Dowell, 2001). This eliminated the possibility of segregation and sampling errors as being the sole source of high recoveries.

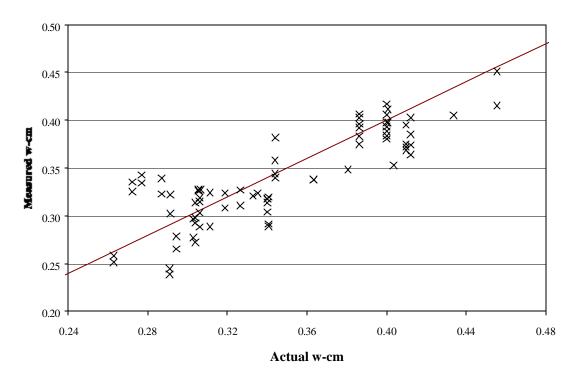


Figure 3-5: Measured vs. Actual W-Cm (Uncorrected) - Field Data

Table 3-4: Comparison of Batch Plant and Paving Site w-cm Measurements

To at Noveles o	Microw	ave w-cm
Test Number	Batch Plant	Paving Site
G-1	0.367	0.371
G-2	0.395	0.367
G-3	0.400	0.380

#### 3.2.3 VARIABLE MOISTURE CONTENTS OF AGGREGATES

It was observed that microwave readings taken in the field had higher variations than those tests performed under laboratory conditions. It was thought that the high recovery values of microwave tests performed in the field could be due to the variability of moisture content of the aggregates used in the field. At most of the batch plants visited throughout this study, the moisture content of the aggregates was taken twice a day, once in the morning and once in the afternoon. These samples were then dried and the moisture content reported to the batch plant operator. The updated moisture contents were usually not incorporated into the mix design for half a day or longer. For example, a moisture content sampled in the morning would not be updated in the mix design until late morning or early afternoon.

In order to get an idea of the water variation that was present in the microwave method, the plots of measured vs. actual w-cm were investigated (Figure 3-6). The maximum and minimum variation from the line of perfect agreement was determined for both the laboratory and field data sets. It was observed that the lower value of variation was similar for both data sets after outliers were removed. The difference in the maximum variations for the field and laboratory data sets represent the maximum amount of unexplained water variation in the

aggregates in the field that needed to be explained. The difference between the intercepts of these lines was 0.052. This value of w.cm, translates into a water variation of 52.9 lb/yd<sup>3</sup> assuming that the cement measurement is accurate.

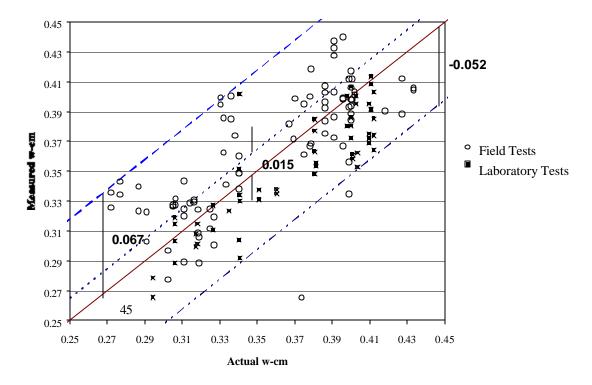


Figure 3-6: Measured vs. Actual Water-Cementitious Ratio for All Microwave Tests

In order to assess the variability of aggregate moisture contents at a concrete batch plant, a batch plant was visited and the aggregate moisture content was tested every hour for one day. The weather had been dry for 10 days prior to the testing day and there was a small amount (0.08") of rain the previous evening. On the day of testing the weather was clear and sunny with the temperature ranging from 52° to 72° F. The hourly moisture contents were compared with the moisture content that was reported by the quality management personal at the batch site. In addition, the moisture content used for the mix design was also recorded. At this particular site the moisture content was taken twice daily but it took a while before the moisture content updates were incorporated into the mix design. This was found to be the case for many of the paving sites visited. From this one day visit it was found that the moisture content of the aggregates did vary throughout the day as aggregate from the center and outer edges of the stock pile were used at different times. The variations in water content from what was tested versus what was reported by the quality control personel and used for batching translated into possible water errors of 32.7 lb/yd³ (Table 3-5). The variation within the eight moisture contents taken alone amounted to 22.7 lb/yd³ of water.

The aggregate moisture content was tested on a fairly cool summer's day when the pile was relatively dry. This was not a worse case situation from a moisture variation perspective and in fact approached conditions where moisture variations were minimized. It is thought that the moisture variation would be greater on a warmer day or if the moisture in the pile varies due to significant rain. From this simple study it seems reasonable to conclude that a significant portion

of the differences between field and laboratory microwave data result from fluxuations in the moisture content of the aggregates used in the field. This leads to the conclusion that the microwave wcm are considerably more accurate than the field standard errors suggest. Field performance of the microwave likely approaches a similar level of error realized in the laboratory.

Table 3-5: Variations in Aggregate Moisture Contents (Batch vs. Hourly MC)

	Average % Difference in MC (measured – actual)	Average Change in Water (lb/ft <sup>3</sup> )
Sand	0.9%	10.8
<sup>3</sup> / <sub>4</sub> " Coarse Aggregate	1.6%	17.6
1 ½" Coarse Aggregate	0.6%	4.3

#### 3.2.4 MEAN AND STANDARD ERROR

The mean error of all microwave method results is 0.012 (microwave w-cm – batch w-cm) indicating that on average the microwave method results are higher than indicated on the batch sheets (Figure 3-7). As the results are split into two groups for the laboratory and field mixes a division is observed. The mean error of the laboratory tests was 0.000 (Figure 3-8) while the error of the field tests was 0.023 (Figure 3-9). This indicates that the mean error for the method in the laboratory, as developed and adjusted in this research, is zero. The experienced errors will range about the mean averaging zero. All of the data resembles a normal curve, which re-affirms the validity of the statistics. The analysis of the means affirms the earlier observation that field tests recovered more water than the batch sheets indicated.

Table 3-6: Average Microwave Oven Method Standard and Mean Errors

Project	Mean Error (microwave – batch)	SE
All	0.012	0.030
Field	0.023	0.037
Lab	0.000	0.027

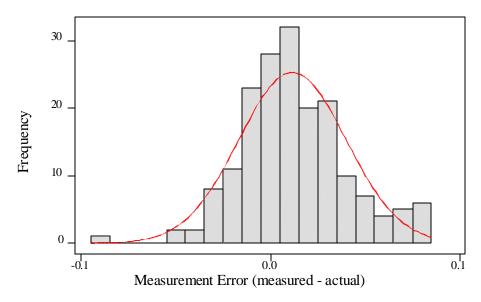


Figure 3-7: Histogram of Microwave Oven Errors for All Mixes

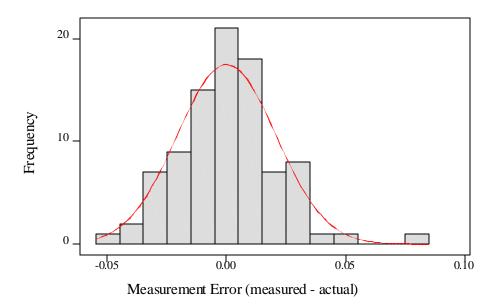


Figure 3-8: Histogram of Microwave Oven Errors for Laboratory Mixes

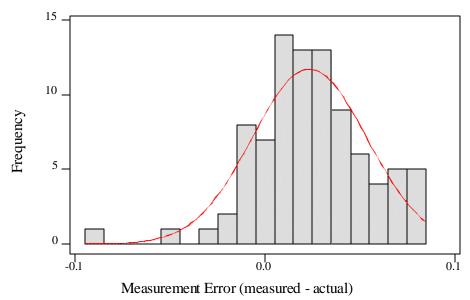


Figure 3-9: Histogram of Microwave Oven Errors for Field Mixes

As discussed above, it is believed that the batch sheet quantities that were used for the calculation of errors in the field projects contain errors. These batch sheet quantities are used are compared to the measured values reported by the microwave oven method to yield standard errors for each project. These standard errors appear higher (Table 3-7) since they represent errors in the test method as well as errors in the batch sheets used for comparison. Furthermore, it is theorized that the standard errors for the field projects would approach the level of error experienced in the laboratory if more precise measures of the batch constituents were used for comparison. The average error for the microwave method in the field was 0.037.

Similar to the laboratory calculations, the w-cm results from the two concrete samples taken from each batch were averaged. With this calculation, the standard errors decreased slightly (Table 3-7).

Project	Field SE	Average of Test 1 & Test 2 SE
A	0.072	0.071
В	0.032	0.029
С	0.040	0.040
D	0.026	0.026
Е	0.036	0.033
F	0.030	0.019
G	0.020	0.017
Average	0.037	0.035

It has been suggested that a method of determining the w-cm of fresh concrete in the field within 0.02 of the true value would be acceptable for use as a quality control measure in practice. Given the analysis of both the field and laboratory microwave oven method results, the lowest standard deviation of the error than can be practically expected is approximately 0.02. If

repeated tests are performed on each concrete batch, the likelihood of outlying results are decreased as the results are averaged. The microwave oven method appears to accurately detect water content of concrete samples and barely meets the threshold of 0.02.

#### 4 NUCLEAR GAUGE RESULTS

#### 4.1 Introduction

The Troxler Water-Cement gauge was used to test concrete both in the field and the laboratory. Once the laboratory calibration was complete, the field data could be interpreted and errors assessed. The gauge performed well for some mix designs yielding standard errors similar or less than those found with the microwave oven method under laboratory conditions. Errors for the data taken in the field were generally higher than those obtained in the laboratory, but likely for the same reasons as discussed for the microwave oven method. Mixes containing igneous aggregates yielded large errors both in the laboratory and the field.

# 4.1.1 WITHIN TEST VARIABILITY

Two nuclear gauge readings were run on each batch of concrete both in the field and in the laboratory. The nuclear gauge bucket was only filled once for each concrete batch, but two nuclear gauge readings were taken consecutively. By doing this, the minimum variability of the method was assessed. The results from the two tests were compared to each other using an ANOVA analysis (Dowell 2001). The analysis of the two tests showed no significant difference between the two tests. However, some variation was observed and theorized to be the variability of the gauge measurements themselves. The standard deviation of the error between the two tests was determined and referred to as the minimum standard error. The minimum standard error for the water probe was determined to be 10.0 lb/yd<sup>3</sup>. A difference was noted between the minimum cement content errors for mixes that contained igneous and limestone aggregates. The minimum cement content error for mixes containing limestone aggregates was 24.7 lb/yd<sup>3</sup>. The minimum cement content error for igneous mixes was higher at 46.4 lb/yd<sup>3</sup>. Likewise, the w-cm error for limestone mixes was relatively low at 0.018 and higher for igneous mixes at 0.072. Since the concrete remains in the testing bucket, and previous research (Santos, 1999) demonstrated that wait time did not have a significant effect on the gauge readings, sampling was not an issue and the consecutive tests on the same concrete sample yielded the variability inherent in the gauge.

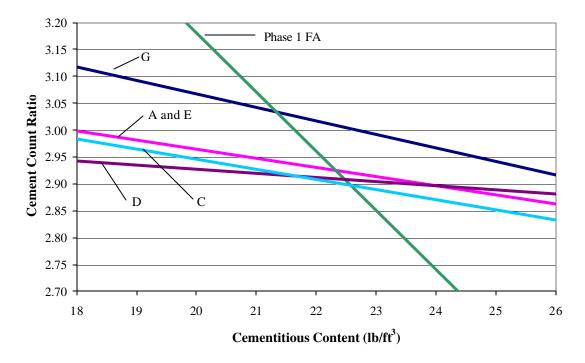
#### 4.2 Nuclear Gauge Laboratory Results

In order to interpret the results of the nuclear gauge in the field, a laboratory calibration must be performed for each mix design. Laboratory calibration mixing was completed for five of the projects, A, C, D, E, and G. Full laboratory calibrations were not performed on Projects B and F due to material quantity constraints.

#### 4.2.1 CEMENT PROBE

The calibration for the cement probe was performed with the materials from four of the paving sites. Projects A and E represent testing at the same paving site on two different dates. Therefore, the aggregate was the same for both projects and the calibration could be applied to both sets of data. Cement probe calibrations were completed for projects C, D and G as well. The target mixes and the four modified cement content mixes for each job were mixed in the laboratory at WSTML and tested with the Troxler Nuclear Gauge. The cement count ratios

obtained from testing the modified cement content mixes and the target mixes were plotted against the batch content of cement and fly ash to obtain regression lines (not shown, see Dowell 2001). The regression lines from each project were compared to one another and to the slope obtained in the first phase of this study (Figure 4-1). As expected, the slopes of the cement probe calibrations varied, due to differences in aggregate mineralogy and cementitious materials.



**Figure 4-1: Cement Probe Calibrations** 

The standard errors of the laboratory mixes were quite high compared to the accuracy suggested by the Troxler gauge operator's manual. The standard error for the cement probe ranged from 11.6 to 45.3 lb/yd<sup>3</sup> (Table 4-2). The Troxler gauge operator's manual reports that the gauge is capable of determining the cement content to within 8.5 lb/yd<sup>3</sup>. The HITEC (1996) report on the nuclear gauge reports a standard error of 13.7 lb/yd<sup>3</sup> for the cement probe.

The minimum error for the cement probe was calculated by comparing the cement probe predictions from the two nuclear gauge tests performed on each batch of concrete. Since the nuclear gauge sampling bucket was not refilled before the second nuclear test, the minimum error only represents the variability of the gauge, not the sampling error. A difference was noted between the minimum error for mixes containing limestone and igneous aggregates. The minimum cement content standard errors for limestone mixes was 27.4 lb/yd³ and 46.4 lb/yd³ for igneous mixes.

# 4.2.2 DIFFERENCE BETWEEN PHASE 1 AND PHASE 2 CALIBRATION SLOPES

A major difference was noted between the slopes of the cement probe regressions obtained from this study and the slopes of the lines from the first phase of the study on the Troxler nuclear gauge (Santos, 1999). In the first phase of this study, the focus was placed on the measurement of the water in a mix. By adjusting the amount of water in the mix, the w-cm varied. Mixes with three levels of w-cm were tested and used for calibrating the water probe.

However, the variation in cementitious content as the water content varied was smaller than the 100 lb/yd<sup>3</sup> variation recommended by Troxler (Figure 4-2).

While the data from Phase I indicated a relatively high slope for the cement probe calibration, the range of the data was insufficient to accurately establish the slope. To determine an accurate slope for the Phase I calibration, two mixes were completed in the laboratory with the recommended 100 lb/yd³ variation in cement content and a target mix from Phase I was repeated. The target mix from Phase I was repeated to ensure that there was no significant change in mixing technique or significant radioactive decay of the nuclear gauge's radioactive source accounting for variation. The nuclear gauge data taken from these two mixes found that the slope of the cement probe calibration for Phase 1 is in the range of the slopes found in this current study (Figure 4-3).

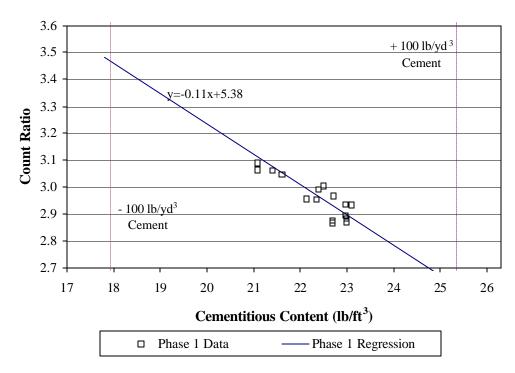


Figure 4-2: Phase 1 – Cement Probe Calibration (Data from Santos, 1999)

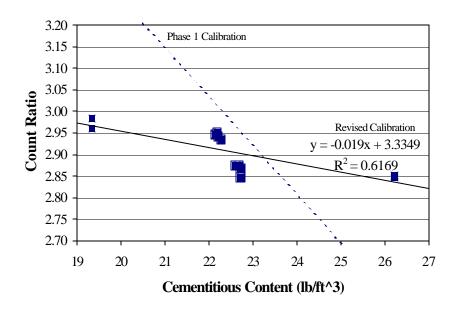


Figure 4-3: Revised Cement Probe Calibration for Phase 1

#### 4.2.3 WATER PROBE

Water calibrations were completed for four of the projects. As with the cement probe, a single calibration applied to projects A and E since the paving took place at the same location and with the same aggregate source. Water calibrations were also completed for projects C, D, and G. While the slopes of the lines are similar, the intercepts of the calibration lines differ (Figure 4-4).

The standard errors of the water contents determined by the nuclear gauge were much higher than reported by the gauge manufacturers. Errors in the water probe ranged from 8 to 36 lb/yd³ (Table 4-3). The Troxler manufacturer reports that the water probe is able to detect the water in a mix to within 1.02 lb/yd³. The HITEC report on the nuclear gauge, reports water errors of 3.7 lb/yd³. Communications exchanges with the gauge manufacturer were unable to resolve these higher errors encountered in this study.

The minimum error was established for these mixes by comparing the results from the two nuclear gauge tests. The minimum error for the water probe was 10 lb/yd³ for mixes containing both igneous and limestone aggregate in the field.

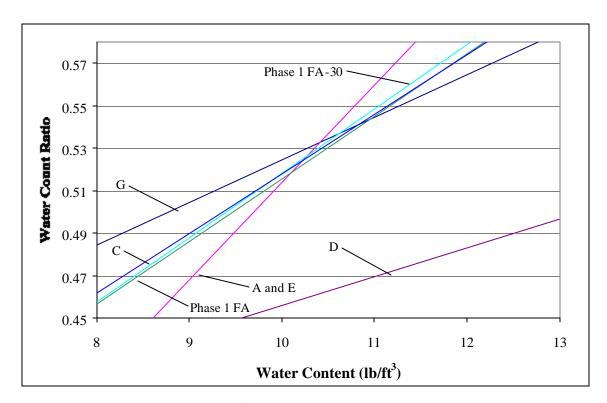


Figure 4-4: Water Probe Calibrations

# 4.2.4 WATER-CEMENTITIOUS MATERIAL RATIO

From the calibration lines for the water and cementitious content for each project a predicted water-cementitious ratio was calculated. The water-cementitious ratios for laboratory mixes were compared to the w-cm as obtained from the batch sheets.

The minimum error in wcm was determined by comparing the wcm results from the two nuclear gauge tests from each batch of concrete. The minimum standard error in w-cm was 0.018 for limestone mixes and 0.072 for igneous mixes.

Projects A, C, and E used limestone aggregates and Projects D and G used igneous aggregates. The standard errors of mixes containing limestone aggregates were low (Table 4-1). For the mixes using limestone aggregate the errors for the nuclear gauge were lower than the microwave method. However when the nuclear gauge was used with igneous aggregates the standard errors increased significantly. It is theorized that the standard errors for mixes containing igneous aggregates are higher than limestone aggregates due to the chemical composition of the aggregates. It appears that some feature of the igneous aggregate is affecting the operation of the nuclear gauge. However, it is theorized that the errors experienced with igneous mixes were random in nature since the calibration did not reduce the errors.

Table 4-1: Standard Error of Water-Cementitious Ratio for Laboratory Mixes (SE for nuclear gauge based upon batch water content)

	Aggregate Type	Nuclear Gauge SE of w-cm	Microwave SE of w-cm
A and E	Limestone	0.010	0.017
С	Limestone	0.014	0.030
D	Igneous	0.066	0.026
G	Igneous	0.046	0.015

## 4.2.5 ALTERNATIVE CALIBRATION – PURE TESTS

The calibration method of mixing eight concrete mixes in the lab with modified cement and water contents was laborious and difficult to complete with accuracy. Even in the controlled environment of the laboratory, it was difficult to produce mixes within the specified air content. In an attempt to find an alternative method of calibrating the nuclear gauge that did not involve mixing concrete, during Phase I we introduced the concept of performing calibration by individually testing the constituents of the concrete mix and then adjusting for batch quantities. In Phase II we attempted to refine and develop this concept.

It was hypothesized that if each individual material was tested with the nuclear gauge that the resulting count ratios would provide information on the role that each material plays in the count ratio of a concrete mix made with the individual materials. It was hoped that the individual material count ratios in combination with the mix design could be algebraically combined to yield a count ratio close to the count ratio of the combined concrete mix. The individual material's count ratio would in effect account for the base reading of the material. Material tests could be adjusted if a new material was substituted in the mix design.

To test the individual material's count ratio, dry materials were placed in the gauge bucket and weighed to determine the unit weight. A standard gauge reading was then taken on each individual material separately. The count ratios from the cementitious materials, aggregates, and water in addition to the batch information and unit weights were combined algebraically to yield an experimental count ratio for the concrete mix. Using a trial and error method, various functions of count ratio, unit weight, and batch proportions were investigated that combined the individual material count ratios and the batch information yielding a combined count ratio for a mix (Equation 4.2-1).

$$Combined \_Count = f_1(C_{cement}) + f_2(C_{fly\_ash}) + f_3(C_{coarse\_agg}) + f_4(C_{fine\_agg}) + f_5(C_{water})$$
 Eq. 4.2-1

Where  $C_{cement} = cement count ratio$ 

 $C_{fly\_ash} = fly ash count ratio$ 

 $C_{coarse\_agg} = coarse$  aggregate count ratio

 $C_{\text{fine\_agg}} = \text{fine aggregate count ratio}$ 

 $C_{water}$  = water count ratio

These experimental combined count ratios were then compared to the count ratios found from testing the concrete mix. Many algebraic and trigonometric functions for combining the pure test data and the batch data were tried, but the associated standard errors were very large. It

was concluded that the development of an alternative calibration with pure test data was not promising and this effort was terminated.

## 4.3 NUCLEAR GAUGE FIELD RESULTS

After the laboratory calibrations were complete, they were applied to the field mixes. Errors in the field generally appeared much greater than those in the lab. The batch quantities reported in the field were variable in nature due to the shifts in moisture content of the aggregates. Thus, the standard errors reported for the field reflect error due to batching, gauge measurement, and sampling in addition to nuclear gauge associated errors.

# 4.3.1 CEMENT PROBE

Comparing the standard errors of the laboratory and the field tests some trends were noticed. The standard errors in the field ranged from 34.8 to 130.7 lb/yd<sup>3</sup>, considerably higher than the laboratory range of 11.6 to 45.3 lb/yd<sup>3</sup>. The range in standard errors in the field translates into 6 to 22% of the cement added to an A-FA mix.

Project	Laboratory Standard Errors (lb/yd³)	Field Standard Errors (lb/yd³)
A	27.6	34.8
С	21.6	49.4
D	45.3	130.7
E	27.6	81.6
G	11.6	41.4
Phase 1 initial calibration	12.6	-
Troxler specifications	<u>+</u> 8.5	-
HITEC Report (1996)	14.6	-

**Table 4-2: Cement Probe Standard Errors** 

#### 4.3.2 WATER PROBE

Water probe standard errors for the field mixes were significantly higher than most of the laboratory mixes (Table 4-3). All standard errors for the water probe were higher than the Troxler gauge manual recommended. Again, the trend was attributed to changes in the moisture content of the aggregates, gauge measurement, or sampling.

Table 4-5: Water Frobe Standard Errors				
Project	Laboratory Standard Errors	Field Standard Errors		
	$(lb/yd^3)$	$(lb/yd^3)$		
A	8.0	42.8		
С	18.9	22.3		
D	36.0	80.1		
E	8.0	26.2		
G	8.0	14.4		
Phase 1 initial calibration	19.4	-		
Troxler specifications	<u>+</u> 1.02	-		
HITEC Report (1996)	3.7			

**Table 4-3: Water Probe Standard Errors** 

#### 4.3.3 WATER-CEMENTITIOUS MATERIAL RATIO

Mixes performed in the field generally had higher standard errors in w-cm (with the exception of Project G) than the laboratory mixes (

Table 4-4). The distinction noted between the errors of laboratory igneous and limestone aggregates was not as pronounced in the field mixes.

	Aggregate	Nuclear	Microwave				
	Type	Gauge	SE of w-cm				
		SE of w-cm					
A	Limestone	0.054	0.072				
С	Limestone	0.042	0.032				
D	Igneous	0.089	0.026				
Е	Limestone	0.064	0.036				
G	Igneous	0.012	0.020				

Table 4-4: Standard Error of Water-Cementitious Ratio for Field Mixes

## 5 STRENGTH RESULTS

#### 5.1 LABORATORY STRENGTH RESULTS

Water-cementitious ratio of Portland cement concretes plays the primary role in determining the compressive strength. According to Abram's Law (Abrams, 1918) as the w-cm increases, the strength, all other factors remaining constant, decreases. For four projects (A, B, E, and F) the mixes completed in the laboratory did not have a large range of w-cm variation. The range in w-cm for these projects was not sufficient for the relationship between strength and w-cm to be pronounced. Extensive laboratory compressive strength testing was completed for three of the projects (C, D, and G) that had larger ranges in w-cm variation. The compressive strengths of cylinders from these laboratory mixes were plotted against the w-cm reported on the batch sheets and the two experimental w-cm's from the methods being studied. All three projects individually displayed the expected relationship between w-cm and compressive strength in the laboratory (Figure 5-1, Figure 5-2, Figure 5-3). As the w-cm increased, the compressive strength decreased as expected for all plots of the laboratory data. In order to determine which method had the highest correlation between strength and w-cm, the coefficients of determination (R<sup>2</sup>) were inspected for each set of data. For two of the three projects (C and D), the batch sheet information provided the w-cm that had the best correlation with the compressive strength. For the third project, the coefficients of determination were about the same for the batch sheet and the microwave oven method. Given the expectation that Abrams' Law will govern the strengths, it can be concluded that the batch weight information provides the most accurate determination of w-cm in the laboratory. In distinguishing between the two experimental methods, neither demonstrated compelling evidence of the relationship between wcm and compressive strength. The coefficients of determination were low for most of the microwave and nuclear results. It did not appear feasible to use either of the two experimental methods as a replacement for strength testing.

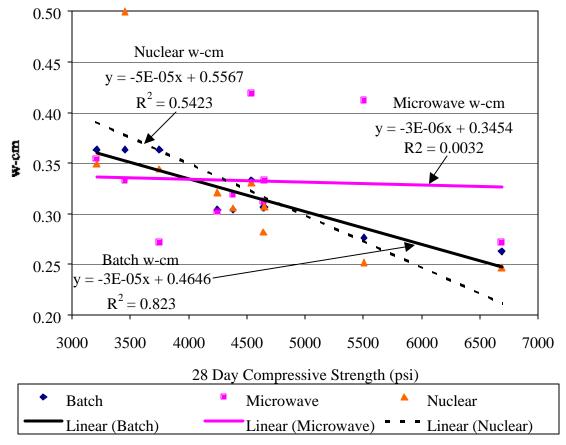


Figure 5-1: W-cm vs. Compressive Strength - Project C - Laboratory Data

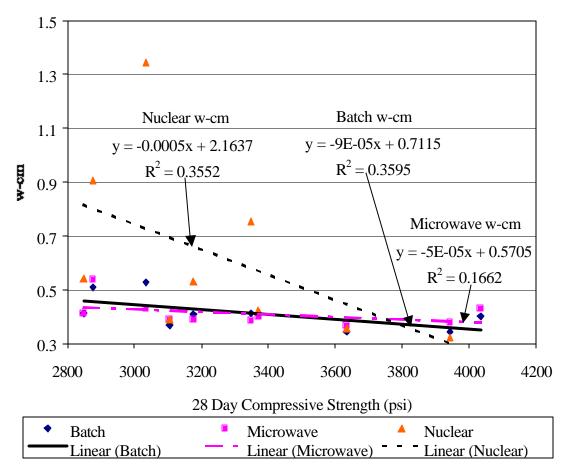


Figure 5-2: W-cm vs. Compressive Strength – Project D – Laboratory Data

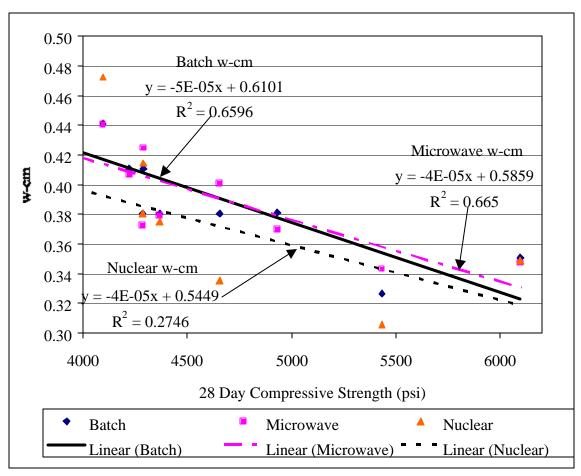
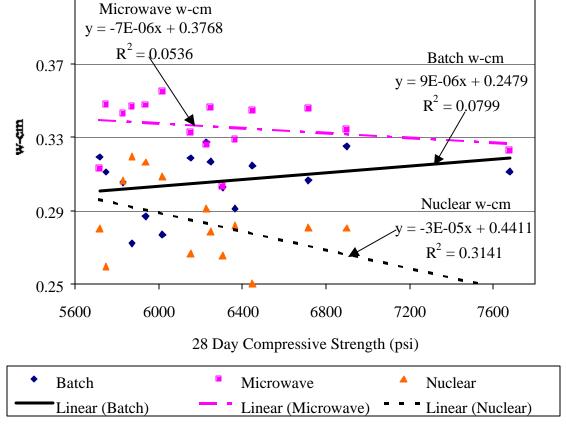


Figure 5-3: W-cm vs. Compressive Strength – Project G – Laboratory Data

#### **5.2 FIELD STRENGTH RESULTS**

The w-cm reported on the batch sheets and determined by the microwave and nuclear gauge are plotted against compressive strength for the field mixes (Figure 5-4, Figure 5-5, Figure 5-6). These plots did not display a strong relationship between w-cm and strength for most projects. The coefficients of determination were generally higher for the experimental methods than the batch sheets. This confirms the theory that errors with the batch sheets in the field were the source of conceived errors with the experimental methods in the field. The nuclear gauge and microwave oven were detecting the materials in the mix to a greater accuracy than the batch sheets report.



0.41

Figure 5-4: W-Cm vs. Compressive Strength - Project C - Field Data

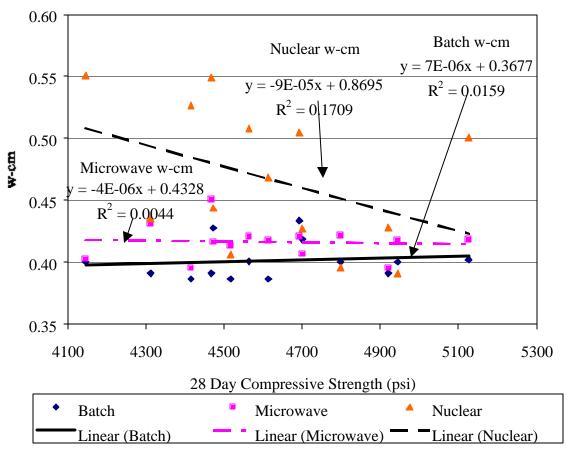


Figure 5-5: W-Cm vs. Compressive Strength – Project D – Field Data

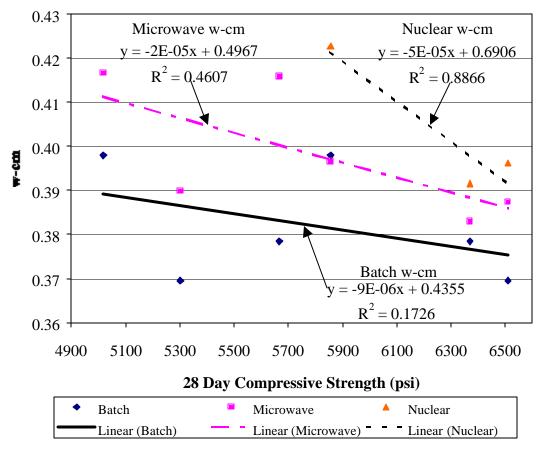


Figure 5-6: W-Cm vs. Compressive Strength – Project G – Field Data

#### **6 SUMMARY AND CONCLUSIONS**

## 6.1 SUMMARY OF MICROWAVE OVEN METHOD RESULTS

The microwave oven method was evaluated at seven concrete paving sites and with corresponding mixes in the laboratory. The standard error in predicting the water-cementitious ratio ranged from 0.014 to 0.030 for laboratory mixes and 0.026 to 0.072 for field mixes. The mean error for laboratory tests was zero indicating that an experimental result has equal likelihood of being high as low. Since two samples were taken from each concrete batch, a measure of the test method error was obtained for the microwave oven method. The minimum error determined by the repeated tests was 0.023 for laboratory mixes. It was concluded that 0.02 is a minimum standard error that can be expected when using the microwave with one sample. As the results from the two samples were averaged, the standard errors decreased to 0.017. This indicates that a large portion of the error calculated for the method is due to sampling errors and is inherent in the testing method. It is theorized that the error could be further reduced by testing more than one small sample or by using a larger sample size.

A number of correction factors were analyzed to determine their effectiveness in reducing the SE of the predicted water-cementitious ratio. A correction factor proposed by INDOT was found to be ineffective in some situations and was abandoned. A correction for the amount of mortar in the microwave sample was applied to the data but found not to consistently improve

upon the standard error and was not used in final calculations. Some field mixes were found to have recovery values greater than 100%. Normally the moisture content is measured twice a day at concrete paving plants. A batch plant was visited and the moisture content of the aggregates was measured hourly. The variation experienced during the day when compared to the values used for the mix design was of the same magnitude as the difference in water content between field and lab mixes. It was concluded that a large portion of the errors in the microwave oven method in the field are due to the inaccuracies in the moisture content of the aggregates, not a problem with the method exclusive to field conditions.

#### **6.2 MICROWAVE OVEN RECOMMENDATIONS**

The microwave method was a simple method that can be implemented with reasonable ease. The accuracy of the method is borderline useful largely because of the small sample size and likely would need to be supplemented with repeated tests and averaging for field use. The inability to predict compressive strength and for this method to be a viable alternative to compressive strength testing is a serious limitations. At the current time, this research does not support implementation of the method.

#### 6.3 SUMMARY OF NUCLEAR GAUGE RESULTS

The Troxler water-cement gauge was used in the field to test the concrete at the seven paving sites. Materials were returned to the Wisconsin Structures and Material Test Laboratory (WSMTL) at the University of Wisconsin-Madison for calibration of the nuclear gauge. In order to interpret the data taken in the field, calibration mixes were completed for five of the project sites. Calibrations were not completed for the other two project sites due to material constraints. The calibrations of the water and cement probes yielded experimental contents for each of the field and laboratory tests. The errors in the cement and water predictions were high when compared to other research done on the nuclear gauge (HITEC, 1996) and the measurement specifications of the gauge. The experimental w-cm was calculated using the experimental water and cement contents. The standard error of the water and cement contents partially cancelled one another to yield standard errors of the w-cm in the range of 0.010 to 0.066. A distinction was noticed between mixes containing limestone and igneous aggregates. The nuclear gauge method resulted in standard errors of 0.010 and 0.014 for limestone mixes, but the errors were significantly higher for igneous mixes. The standard errors of the two mixes containing igneous aggregates were 0.046 and 0.066. Standard errors of the field mixes were much higher and ranged from 0.012 to 0.089.

The data from the two consecutive tests performed on the nuclear gauge revealed the error inherent in the nuclear gauge method. This within test error in w-cm was 0.018 for limestone mixes and 0.072 for igneous aggregates. This value compared to the standard errors experienced with testing suggests that the majority of the error is inherent to the method or the particular gauge that was used. For some reason, the errors of igneous mixes are very high indicating that the Troxler water-cement gauge should not be used with mix designs that use igneous aggregates. The errors associated with limestone mixes are much lower and yield errors comparable to the microwave oven method.

#### **6.4 Nuclear Gauge Recommendations**

While the nuclear gauge provides satisfactory results for mixes with limestone aggregate, it is unknown why igneous aggregates produce large errors in this research. Given the NRC

training and certification and labor-intensive calibration procedure, it does not appear that the method meets the needs of the concrete pavement industry.

# **6.5 CONCLUSIONS**

- 1. Microwave is a reliable method for determining the w-cm of concrete but care and control are needed to limit errors. Approximately 68% of the error measurements will be in the range of + 0.02 of the mean error. The mean error for laboratory mixes was zero.
- 2. Standard errors of the microwave oven method for field mixes were higher than the laboratory. It is believed that the microwave oven method accurately detected the water in the sample. The variability of the batch ticket quantities and within mix water variability led to apparently higher w-cm errors for the microwave oven method in the field.
- 3. Errors in the microwave oven method could be improved by increasing the sample size or by averaging the results from multiple small samples.
- 4. The nuclear gauge provided accurate results for limestone mixes in the laboratory and potentially in the field. After calibration, the nuclear gauge is capable of determining the w-cm errors within  $\pm$  0.01 of the mean. However, the certification and calibration procedure renders the nuclear gauge difficult for general use in paving construction.
- 5. The nuclear gauge provided inaccurate results when used with mixes containing igneous aggregates.
- 6. There was poor correlation between the w-cm determined by either the nuclear gauge or the microwave and the compressive strength of the concrete. In the field, however, the two experimental methods predicted strength better than general batch quantities. Neither of the experimental methods reliably predicted compressive strength.

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#### **REFERENCED STANDARDS:**

AASHTO TP23-93 Edition 1A. Standard Test Method for Water Content of Freshly Mixed Concrete Using Microwave Oven Drying

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- ASTM C 127-93, Standard Test Method for Specific Gravity and Absorption of Coarse Aggregate, Vol. 04.02.
- ASTM C 128-97, Standard Test Method for Specific Gravity and Absorption of Fine Aggregate, Vol. 04.02.
- ASTM C 138-92, Standard Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete, Vol. 04.02.
- ASTM C 143-97, Standard Test Method for Slump of Hydraulic Cement Concrete, Vol 04.02.
- ASTM C 231-97, Standard Test Method for Air Content of Freshly Mixed Concrete, Vol. 04.02.
- ASTM C 566-97, Standard Test Method for Total Evaporable Moisture Content of Aggregate by Drying, Vol. 04.02.
- ASTM C 1064-93, Standard Test Method for Temperature of Freshly Mixed Portland Cement Concretes, Vol. 04.02.

# **IMPLEMENTATION PLAN**

WisDOT Research

Wisconsin Department of Transportation 4802 Sheboygan Ave., Rm. 451 P.O. Box 7965 Madison, WI 53707-7965 www.dot.state.wi.us/dtid/research Nina McLawhorn, Research Administrator Ann Pahnke, Program Analyst Linda Keegan, Program Analyst Louis Bearden, Program Analyst Pat Casey, Communications Consultant

# **Implementation of Research Results**

Project Information						
Project Title: Field Measurement of Water-Cement Ratio for	Project ID: #0092-45-16 Today's Date:					
Portland Cement Concrete - Phase II Field Evaluation and						
Development						
Technical Oversight Committee (WHRP or COR):	TOC Chair and Phone number:					
	David Larson 608-246-7950					
Project Start Date:	Approved Contract Amount:					
Project End Date:	Final Project Expenditures:					
Reference Final Report Draft Dated:						
Principal Investigator: Steven M. Cramer	Phone: 608-262-7711					
Organization: University of Wisconsin-Madison	E-Mail: cramer@engr.wisc.edu					
TECHNICAL OVERSIGHT COMMITTEE RECOMMENDATIONS						
1. CHECK ONE OF THE TWO CHOICES BELOW:						
$\square$ YES. WE RECOMMEND CHANGES TO CURRENT PRACTICE BASED ON						
RESEARCH WAS SOUND, AND THE REPORT'S CONCLUSIONS AP						
X No. We do not recommend changes to current practice	at this time. This approach does not appear					
fruitful OR future study is needed OR our objectives have changed, etc.						
2. IF IMPLEMENTATION IS NOT RECOMMENDED, WE SUGGEST THE FOLI	OWING ACTIONS INSTEAD:					
3. IF IMPLEMENTATION IS RECOMMENDED, WE SUGGEST THE FOLLOWI	NG SPECIFIC CHANGES TO CURRENT PRACTICE, DETAILED ON					
3. IF IMPLEMENTATION <u>IS RECOMMENDED</u> , WE SUGGEST THE FOLLOWING <u>SPECIFIC</u> CHANGES TO CURRENT PRACTICE, DETAILED ON THE <u>ATTACHED WORK PLAN AND TIMELINE</u> (CHECK APPLICABLE ITEMS):						
THE ATTACHED WORKT DAWARD THEEDINE (CHECK ATTECADLE TIEWS).						
$\square$ Standard Specifications						
•	4					
☐ Quality Management Program (QMP) Specifica	itions					
☐ Facilities Development Manual (FDM)						
☐ Highway Maintenance Manual						
☐ Training, outreach						
☐ Other (describe):						
— Other (describe).						

	Signature:						
4. APPROVAL OF THIS IMPLEMENTATION PLAN BY THE							
TECHNICAL OVERSIGHT COMMITTEE (CHAIR ON BEHALF OF	F Date:						
ENTIRE COMMITTEE):	- ****						
5. Approval of this implementation plan by the Council on	Signature(s):						
Research (for COR approved projects):							
	Date:						
6. Referral for development of detailed work plan and	☐ WisDOT/Industry Technical Committee on:						
timeline to (check one):							
	☐ Other WisDOT policy body:						
7. Approval of work plan and timeline by the WisDOT	Signature(s):						
Bureau Director(s) responsible for the policies	Signatur C(S)						
described in item #3 above:	Date						
8. Acceptance by a project manager of the	Signature:						
responsibility for completing these implementation efforts							
according to the attached work plan and timeline:	Date:						

Rev. 4/8/01

IMPLEMENTATION WORK PLAN	
1. Project Title:	2. Prepared by:

1. Scope and objectives of implementation, including specific changes to WisDOT procedures.											
2. Estimated cost (if any) to implement.											
4. Expected benefits and how they will be mea	sure	d (dol	llar sa	aving	s, tim	e sav	ings,	other	·).		
5. Possible pitfalls and how they will be avoide	ed.										
Implementation Timeline (Gantt Chart)											
Tasks/Person Responsible											

Rev. 5/8/01 Page 2 of 2